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FUNDAMENTAL AND APPLIED QUANTUM OPTICS

Principal Investigator: Marlan O. Scully

Texas A&M University

College Station, TX 77802

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Principal Investigator: Marlan O. Scully

Mailing Address: Department of Physics, Texas A&M University; College Station, TX 77843

Phone number: (409)862-2333

Email address: scully@tamu.edu

Fax Number: (409)845-2590

http address:

A Number of Papers submitted to refereed journals, but not published: 9

- [1] V. V. Kozlov, O. A. Kocharovskaya, M. O. Scully, "Effective Two-Level Maxwell-Bloch Formalism and Coherent Pulse Propagation in a Driven Three-Level Medium" (to be published).
- [2] V. V. Kozlov, P. G. Polynkin, M. O. Scully, "Resonant Raman Amplification of Ultrashort Pulses in a V-type Medium" (to be published).
- [3] G. R. Welch, G. G. Padmabandu, J. Liu, P. Polynkin, H. Lee, C. Bednar, M. O. Scully, "Observation of Spontaneous Emission Modification by Quantum Interference" (to be published).
- [4] A. Zibrov, M. D. Lukin, L. Hollberg, M. O. Scully, and V. Velichansky, "Parametric self-oscillation via resonantly enhanced multiwave mixing" (to be published).
- [5] H. Lee, M. F. Fleischhauer, and M. O. Scully, "Sensitive detection of Magnetic field including their Orientation with a Phaseonium magnetometer" (to be published)
- [6] A. Matsko and Y. V. Rostovtsev, "EM-wave Propagation and Amplification in Overdense Plasma: Application to Free Electron Lasers", scheduled for publishing in Phys. Rev. E, December (1998).
- [7] M. O. Scully, "Correlated emission spectroscopy of metastable Hydrogen; how real are the virtual states?" (to be published)
- [8] H. Lee, S.-Y. Zhu, and M. O. Scully, "Resonant enhancement of refractive index in a photonic bandgap structure" (to be published).
M. O. Scully, "Correlated emission spectroscopy of metastable Hydrogen; How real are the virtual states?" (to be published).
- [9] J. A. Bergou, J. Gea-Banacloche, and M. O. Scully, "CEL gyroscope with injected squeezed vacuum" (to be published).

B Number of Papers published in refereed journals (for each, provide a complete citation): 37

1998

- [1] M. D. Lukin, P. Hemmer, M. Löffler, and M. O. Scully, "Resonance enhancement of parametric processes via radiative interference and induced coherence" Phys. Rev. Lett. **81** 2675 (1998).
- [2] A. Vladimirov, P. Mandel, S. Yelin, M. D. Lukin, M. O. Scully, "Nonlinear dynamics in a single mode three-level laser without inversion", Phys. Rev. A **57**, 1499 (1998).
- [3] D. Nikonov, Y. Rostovtsev, and G. Sussmann, "Madey's and Liouville's theorems relating to free-electron lasers without inversion", Phys. Rev. A **57**, 3444 (1998).

- [4] M. O. Scully, "Do Bohm trajectories always provide a trustworthy physical picture of particle motion?" *Physica Scripta* **T76**, 41 (1998).
- [5] M. O. Scully, M. Fleischhauer, E. Fry, A. Imamoglu, M. D. Lukin, D. Nikonov, Th. Walther, and S. F. Yelin, "Lasing without inversion via interference of double-dark resonances in atomic and quantum well systems" (in press, Kluwer).
- [6] Y. V. Rostovtsev, A. B. Matsko, and M. O. Scully, "Electromagnetic-induced transparency and Amplification of electromagnetic waves in Photonic Band Gap Materials", *Phys. Rev. A* **57**, 4919-4924 (1998).
- [7] G. R. Welch, G. G. Padmabandu, E. S. Fry, M. D. Lukin, D. E. Nikonov, F. Sander, M. O. Scully, A. Weis, and K. Tittel, "Observation of V-type Electromagnetically Induced Transparency in a Sodium Atomic Beam" *Found. Phys.* **28**, 621-638 (1998).
- [8] M. D. Lukin, M. Fleischhauer, M. O. Scully, and V. L. Velichansky, "Intracavity electromagnetically induced transparency", *Opt. Lett.* **23** 295-297 (1998).
- [9] S. F. Yelin, M. D. Lukin, M. O. Scully, and P. Mandel, "Gain without inversion in the frequency up-conversion regime", *Phys. Rev. A* **57**, 3858-3868 (1998).
- [10] H. Lee, M. F. Fleischhauer, and M. O. Scully, "Sensitive detection of Magnetic field including their orientation with a magnetometer based on atomic phase coherence", *Phys. Rev. A* **58**, 2587 (1998).
- [11] H. Lee and M. O. Scully "The Physics of EIT and LWI in V-Type Configurations" *Found. Phys.* **28**, 585-600 (1998).

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- [12] M. D. Lukin, M. Fleischhauer, A. S. Zibrov, H. G. Robinson, V. L. Velichansky, L. Hollberg, and M. O. Scully, "Spectroscopy in dense coherent media: line narrowing and interference effects", *Phys. Rev. Lett.* **79**, 2959-2962 (1997).
- [13] M. O. Scully, C. J. Bednar, Y. Rostovtsev, and S.-Y. Zhu, "Counter-counter-intuitive quantum coherence effects", *Phil. Trans. Royal Soc. London A* **335**, 2305-2311 (1997).
- [14] M. O. Scully, U. W. Rathe, C. Su, and G. S. Agarwal, "On enhancing spectral resolution via correlated spontaneous emission", *Opt. Commun.* **136**, 39 (1997).
- [15] S. F. Yelin, C. J. Bednar, and C.-R. Hu, "The role of atomic recoil in micromaser 'Welch Weg' detection", *Opt. Commun.* **136**, 171 (1997).
- [16] H.-J. Briegel, B.-G. Englert, M. O. Scully, and H. Walther, "Atom interferometry and the quantum theory of meaasurement" in *Atom Interferometry* edited by P. Berman, (Academic press, 1997).
- [17] G. M. Meyer, M. O. Scully, and H. Walther, "Quantum theory of mazer I: General theory" *Phys. Rev. A* **56**, 4142-4152 (1997).
- [18] M. Löffler, G. M. Meyer, M. Schröder, M. O. Scully, and H. Walther, "Quantum theory of mazer II: Extensions and experimental considerations" *Phys. Rev. A* **56**, 4153-4163 (1997).
- [19] M. Schröder, K. Vogel, W. Schleich, G. M. Meyer, M. O. Scully, and H. Walther, "Quantum theory of mazer III: Spectrum" *Phys. Rev. A* **56**, 4164-4174 (1997).
- [20] M. Löffler, D. E. Nikonov, O. Kocharovskaya, M. O. Scully, "Strong-field index enhancement via selective population of dressed states", *Phys. Rev. A* **56**, 5014-5021 (1997).

- [21] H. Lee, P. Polynkin, and M. O. Scully, "Quenching of spontaneous emission via quantum interference: Time evolution", *New Developments on Fundamental Problems in Quantum Physics*, edited by M. Ferrero and A. van der Merwe, (Kluwer, 1997).
- [22] E. J. Bochove, G. T. Moore, and M. O. Scully, "Energy gain, stability, and bunching in gas-loaded Hermite-Gaussian, laser LINAC", *Z. Natur. Sec. A-A J. Physical Sciences* **52**, 111-113 (1997).
- [23] C. H. Keitel, H. M. Doss, M. Fleischhauer, L. M. Narducci, M. O. Scully and S.-Y. Zhu, "The dressed state picture in quantum coherence and interference", *Z. Natur. Sec. A-A J. Physical Sciences* **52**, 114-116 (1997).
- [24] G. T. Moore, E. J. Bochove, and M. O. Scully, "Laser LINAC using a lens wave-guide in vacuum", *Z. Natur. Sec. A-A J. Physical Sciences* **52**, 117-119 (1997).
- [25] M. O. Scully and S.-Y. Zhu, "Sudharshan-Glauber P -distribution, Q -distribution, and Wigner W -distribution in correlated-spontaneous-emission lasers", *Z. Natur. Sec. A-A J. Physical Sciences* **52**, 120 (1997).
- [26] A. Wicht, K. Danzmann, M. Fleischhauer, M. O. Scully, G. Müllr, and R.-H. Rinkleff, "White-light cavities, atomic phase coherence, and gravitational wave detectors", *Opt. Commun.* **134**, 431 (1997).

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- [27] A. S. Zibrov, M. D. Lukin, L. W. Hollberg, M. O. Scully, H. G. Robinson, and V. L. Velichansky, "Experimental demonstration of enhanced index of refraction via quantum coherence in Rb", *Phys. Rev. Lett.* **76**, 3935 (1996).
- [28] G. G. Padmabandu, G. R. Welch, I. N. Shubin, E. S. Fry, D. E. Nikonov, M. D. Lukin, and M. O. Scully, "Laser oscillation without population inversion in a sodium atomic beam", *Phys. Rev. Lett.* **76**, 2053 (1996).
- [29] M. O. Scully, "Induced emission due to the quantized motion of ultracold atoms passing through a micromaser cavity" *Phys. Rev. Lett.* **76**, 4144 (1996).
- [30] D. E. Nikonov, M. O. Scully, M. D. Lukin, E. S. Fry, L. W. Hollberg, G. G. Padmabandu, G. R. Welch, V. L. Velichansky, A. S. Zibrov, "Lasing without inversion: A dream come true", *SPIE* **2798**, 342 (1996).
- [31] D. E. Nikonov, M. O. Scully, and G. Kurizki, "Free-electron laser without inversion via transeverse momentum discrimination", *Phys. Rev. A* **54**, 6780 (1996).
- [32] G. S. Agarwal and M. O. Scully, "Ramsey spectroscopy with nonclassical light sources", *Phys. Rev. A* **53**, 467 (1996).
- [33] S.-Y. Zhu and M. O. Scully, "Spectral line elimination and spontaneous emission cancellation via quantum interference", *Phys. Rev. Lett.* **76**, 388 (1996).
- [34] T. Gantsog, G. M. Meyer, M. O. Scully, and H. Walther, "Dynamic control of micromaser and laser emission from driven three-level atoms", *Opt. Commun.* **124**, 579 (1996).
- [35] U. W. Rathe, M. Fleischhauer, and M. O. Scully, "Broadband phase-noise squeezing of travelling waves in electromagnetically induced transparency", *Phys. Rev. A* **54**, 3691 (1996).
- [36] H.-J. Briegel, B.-G. Englert, and M. O. Scully, "Spectral properties of a micromaser: Atomic-beam statistics and the field correlation function", *Phys. Rev. A* **54**, 3603 (1996).
- [37] H. Huang, S.-Y. Zhu, M. S. Zubairy, and M. O. Scully, "Two-time intensity correlation in a driven three-level system" *Phys. Rev. A* **53**, 1834 (1996).

- C** Number of books or chapters submitted, but not yet published: 0
- D** Number of books or chapters published (for each, provide a complete citation): 1

M. O. Scully and M. S. Zubairy, "Quantum Optics", Camb. Univ. Press

- E** Number of printed technical reports/non-refereed papers (for each, provide a complete citation): 0
- F** Number of patents filed: 0
- G** Number of patents granted (for each, provide a complete citation): 0
- H** Number of invited presentations (for each, provide a complete citation): 10

- [1] Conference, Fundamental Problems in Quantum Theory, UMBC.
- [2] Physics of Quantum Electronics (Snowbird, Utah).
- [3] United Nations Winter Colloquium, Quantum Optics (Trieste):
C. J. Bednar, M. Löffler, M. O. Scully, and H. Walther, "Tunneling and the Mazer",
Quantum Interferometry, Proc. of an Adriatic Workshop, VCH, Weinheim (1996).
- [4] University of Pennsylvania Conference, Quantum Well Lasers.
- [5] International Conference, Squeezed States.
- [6] Nobel Symposium on Advances in Quantum Mechanics.
- [7] Japan Conference on Laser Physics.
- [8] Royal Society (London) Conference on Quantum Optics:
M. O. Scully, C. J. Bednar, Y. Rostovtsev, and S.-Y. Zhu,
"Counter-counter-intuitive quantum coherence effects",
Phil. Trans. Royal Soc. London A **335**, 2305-2311 (1997).
- [9] University of Texas Symposium (in honor of M. Fink).
- [10] American Physical Society Plenary Paper.

- I** Number of submitted presentations (for each, provide a complete citation):
0

- J** Honors/Awards/Prizes for contract/grant employees (list attached): 1

- M. O. Scully, Charles Hard Townes Award, 1998;
- M. O. Scully, Distinguished Professor, 1996;
- M. O. Scully, Burgess Chair, 1997;
- O. A. Kocharovskaya, Lamb Medal, 1998
- D. Nikonov, American Institute of Physics short list of 5 best thesis in atomic physics, 1997.
- M. Lukin, Distinguished Graduate Research Award, Texas A&M University, 1998

K Total number of full-time equivalent graduate students and postdoctoral associates supported during this period, under this PR number: 25

Graduate Students: 14
Postdoctoral Associates: 11
including the number of
Female Graduate Students: 2
Female Postdoctoral Associates: 0
the number of
Minority* Graduate Students: 0
Minority* Postdoctoral Associates: 0
including the number of
Asian Graduate Students: 3
Asian Postdoctoral Associates: 2

L Other funding (list agency, grant title, amount received this year, total amount, period of performance and a brief statement regarding the relationship of that research to your ONR grant)

- Texas Advanced Technology Project,
"Novel Solid-State and Semiconductor Quantum Well Lasers Based on LWT",
\$91,900/\$243,800, 1995-97.
- Texas Advanced Research Project,
"New Short-wavelength Lasers Based via Lasing Without Inversion",
\$77,100/\$135,433, 1995-97.
- The Robert A. Welch Foundation,
"Molecular Coherence and Interference Effects in Laser Chemistry and Chemical Lasers",
\$37,000/\$102,000, 1996-1999.
- DOD-Air Force-Rome Laboratory,
"Quantum Coherence in Silicon",
\$43,000/\$43,000, 1996-97.
- National Science Foundation, NATO,
"Short-wavelength Lasers",
\$45,000/\$45,000, 1997.
- NATO,
"Lasing Without Inversion: Stability and Dynamical Behavior",
177,000BF/177,000BF, 1996-1997.
- INTAS,
"Laser Sources of Squeezed Light",
\$32,500/\$65,000, 1997-99.

Part II

- (a) Principal Investigator:
Marlan O. Scully
Department of Physics, Texas A&M University
College Station, TX 77843
- (b) Current Telephone number:
(409)862-2333
- (c) Cognizant ONR Program Officer:
Herschel S. Pilloff
- (d) Program Objective:
Coherence effects in quantum optics have been recently demonstrated to yield: lasing without inversion, ultra large linear and nonlinear susceptibilities accompanied by suppressed absorption as well as ultra high precision spectroscopy. With "in-principle" theory and proof of principle experiments in hand we are now pushing toward deeper understanding of the basic physics and practical realization of these advances.
- (e) Significant Results:

Lasing Without Inversion (LWI)

- i) First experimental demonstration of Lasing Without Inversion in a Rb cell.
Laser oscillation without population inversion was demonstrated experimentally in a V-type atomic configuration within the D_1 and D_2 lines of Rb vapor. It was shown that the effect was due to the atomic interference. The experimental results, as first predicted by careful theoretical analysis, were in a good agreement with detailed calculations.
- ii) First experimental demonstration of Lasing Without Inversion in Na-beam
Laser operation without inversion in a Na-beam with frequency up-conversion was experimentally demonstrated. The realization of LWI in a beam configuration is an important step towards short-wavelength lasers since atomic beams have to be used in this regime to overcome Doppler broadening.
- iii) Short-wavelength experiments in progress; second-generation theory under way.
Raman LWI in Rb vapor has yielded substantial blue light at 422nm in our experiments. The situation is presently analyzed from two points of view: Lasing Without Inversion, and coherence-assisted nonlinear upconversion.
- iv) Detailed theory of frequency upconversion.
We analyze the general conditions and limitations for the realization of frequency up-conversion via Lasing Without Inversion. Based on this analysis we propose a novel class of schemes in which LWI can be achieved via optical- or microwave-frequency driving on a weakly allowed transition. A non-inversion amplification process based on this system is studied with particular emphasis on propagation effects and Doppler broadening. Amplification of both monochromatic and bichromatic fields is considered and a possible implementation in realistic atoms and ions is discussed.
- v) Nonlinear dynamics.
We characterize analytically the nature of the lasing solutions of a laser operating without population inversion. We consider models involving three-level media interacting with a strong driving field and a lasing field in the vicinity of the lasing threshold. We assess the influence of different relaxation and pumping schemes on the dynamics of these lasers. We use the atom-field detuning, the cavity detuning, and the linear gain as bifurcation parameters. Depending on their values, the stable lasing solution is shown to be cw or self-pulsing. We show that the optimal lasing operation

is achieved if both the driving field frequency and the cavity frequency are out of resonance with the atomic frequencies. Physically, the lasing regimes arise from nonlinearly interacting sidebands induced in the lasing medium by atomic interference.

vi) The physics of EIT and LWI in *V*-type configurations.

We review the concepts and the physics behind the electromagnetically induced transparency (EIT) and lasing without inversion (LWI) for various models of the *V*-type configurations.

vii) Resonant Raman amplification of ultrashort pulses in *V*-type medium.

Propagation of a pair of ultrashort coherent pulses in *V*-type medium is studied. Both pulses are supposed to be resonant with corresponding atomic transitions. It is shown, that the resonant character of the atom-field interaction yields "pulse locking", in which two pulses propagate with equal group velocities. Additionally, in the presence of Raman inversion, the system exhibits resonantly enhanced gain for the probe pulse. These two effects add together to decrease the pump laser threshold intensity by orders of magnitude in comparison with conventional (far off-resonant) Raman laser schemes.

viii) Madey's and Liouville's theorems relating to free-electron lasers without inversion.

The small-gain regime of free-electron lasers (FEL) without inversion is considered and seeming contradictions with the traditional theory of FEL are resolved. As a result, a generalized Madey's theorem is obtained for the case of a phase shift given to electrons between the two wigglers. It explicitly demonstrates the contribution of interference of radiation from the wigglers. It is shown, by considering the motion in the phase space, that Liouville's theorem applied to the motion of electrons in a two-dimensional (rather than one-dimensional) real space is consistent with a nonzero integral of the gain over electron energies. These conclusions are crucial for the achievement of orders-of-magnitude improvement in the FEL gain in the case of a large electron energy spread.

ix) Phased Optical Klystron: Beyond the Small-Gain Regime.

A new gain regime of the free electron laser without inversion is considered. Using numerical simulation of the coupled pendulum equation for electrons and Maxwell's equations for the laser field, we investigate the dependence of gain on the electron momentum spread as well as saturation effects. It is shown that gain in the free electron laser without inversion is less dependent on the electronic momentum spread in the large-gain regime and a higher saturation intensity than an ordinary free electron laser. A new regime with an ultra high gain, due to extraordinarily large bunching of electrons, is found. Design of the drift region necessary for the realization of the above effects is studied.

x) EM-wave propagation and amplification in overdense plasmas: application to free electron lasers.

Considering a propagation of electromagnetic waves through overdense homogeneous plasmas, a new regime of amplification of EM-waves with frequencies below the plasma frequency has been found. An application to free electron lasers is suggested.

xi) Amplification of gamma-rays via coherence driven by optical fields

A concept of amplification without inversion has been broaden into gamma-ray range. The principle possibility of the inversionless amplification has been shown via nuclear coherence driven by the optical fields.

xii) Lasing without inversion in Cherenkov free-electron lasers

Quantum theory is applied to interference of emission and absorption in a two-section Cherenkov free-electron laser (FEL). A scheme for absorption cancellation with enhanced gain, which resembles "lasing without inversion" in atomic systems, is proposed. This scheme is based on the adjustment of the phases of electrons and light by appropriate dispersion between the two sections. It enables FEL operation even with a broad electron momentum spread. Such a scheme is interesting in the context of FEL operation in the ultraviolet and X-ray regimes.

xiii) Asymmetries between Absorption and Stimulated Emission in Driven Three-Level Atomic Systems

We establish simple relations between the physical mechanisms which lead to light amplification without population inversion. Two different types of interference, namely, quantum beat-type interference and Fano-type interference, are discussed. Using the dressed-state basis for driven atomic systems, we analyze, for a weak probe field, the absorption and emission profiles in terms of transition rates. Via Autler-Townes splittings the coherent radiation field which drives one of the lasing levels, provides the quantum mechanical two paths of the absorption/emission. On the other hand, the spontaneous emission process in this driving transition has a crucial role in that whether the interference is constructive or destructive. In the Λ system, for example, Fano-type interference leads to the absorption cancellation and the quantum beat-type interference shows increase of stimulated emission. In the V system absorption is decreases by the quantum beat-type interference and stimulated emission is enhanced by the Fano-type interference. Opposite effects are shown for the cascade-type systems. The results are compared with the density matrix analysis, which shows full agreements.

xiv) Mode locking in a coherently driven laser system.

A new concept of mode locking for a three-level gain medium is proposed. Broadening of the lasing transition by a strong field applied on the coupled transition allows to generate the pulses, that are considerably shorter than the conventional limit imposed by the inverse amplified bandwidth. Maxwell-Bloch type formalism is developed to describe different time-dependent phenomena in the driven system.

Phaseonium

i) First experimental demonstration of high index of refraction.

We demonstrated the index enhancement via quantum coherence for the first time experimentally in a Rb cell. We proposed a new type of active laser magnetometer based on intracavity electromagnetically induced transparency. In contrast to many conventional methods, our technique was shown to be free of power broadening allowing us to overcome the signal-to-noise ration of many current techniques in the strong field regime.

ii) Coherent preparation of double-dark states.

We predict the possibility of sharp, high-contrast resonances in absorption or emission of a broad class of systems, where quantum superposition states ("dark states") are altered in a coherent way. The optical properties of these resonances can be manipulated to design a desired atomic response. This provides a new approach to index enhancement in dense Rb vapor utilizing engineering of dressed atomic states accomplished by coherent preparation with coherent laser and RF drive fields.

iii) Strong-field index enhancement via selective population of dressed states.

A three-level Lambda scheme is proposed in order to achieve a large (resonant) index of refraction with vanishing absorption. This scheme is based on the selective population of one of the dressed states produced by a strong laser field. For modest values of the density and realistic atomic parameters the present scheme gives the index to absorption ratio (approximate)2500. It is to be noted that an off-resonant two-level scheme can also give such a ratio but the index of refraction will be smaller. The present approach to index enhancement is not limited to weak fields, as is the case in some other schemes.

iv) Resonant enhancement of refractive index in photonic band gap systems.

We investigate the dispersive properties of an ensemble of coherently driven three-level atoms in a modified reservoir such as photonic band gap system. We found that the index of refraction can be enhanced more than in normal vacuum reservoir. Furthermore, it suffers less from the absorption of the driving field which maintains the atomic coherence.

v) Sensitive detection of magnetic fields including their orientation with a phaseonium magnetometer.

An optical magnetometer based on electromagnetically induced transparency (EIT) is analyzed. Utilizing the different orientation characteristics for different field polarizations the magnitude

and orientation of an applied magnetic field can be measured. As a model system we consider the sodium D_1 transition taking into account hyperfine structure and optical effects.

vi) Counter-counterintuitive Quantum Coherence Effects

The study of an ensemble of phase-coherent atoms has recently lead to interesting theoretical innovations and experimental demonstrations of counterintuitive effects such as electromagnetically induced transparency (EIT), lasing without inversion (LWI), enhancement of index of refraction, and ultra-large nonlinear susceptibility. We report a couple of new effects along these lines. In fact, it would be fair to call them surprises even in the repertoire of "counterintuitive effects", i.e., "counter-counterintuitive effects". Specifically, we will show that the LWI concept, which is based on quantum coherence, has a surprising counterpart in the classical physics of free electron laser operation. Also, we find that it is possible to "lock" atoms in an excited state via atomic coherence. It is, by now, not surprising that such a phase-coherent ensemble can show holes or dark lines in the emission spectrum. It is surprising that we can lock atoms in an excited (normally decaying) state via atomic coherence and interference. Such a phase-coherent collection of atoms, i.e. "phaseonium", is indeed a novel new state of matter.

Nonlinear optics

i) First observation of nonlinear backward-wave oscillator.

We describe and demonstrate an efficient process of parametric self-oscillation in Raman-like, near-resonant systems driven by counter-propagating fields. Such oscillation does not require optical cavity and manifests itself as a comb of Stokes and anti-Stokes components separated by a two-photon Raman transition frequency. This process can be viewed as a spontaneous formation of atomic coherence grating.

ii) Applications of coherent Raman scattering.

Spectroscopic properties of coherently prepared, optically dense atomic media are studied experimentally and analyzed theoretically. It is shown that in such media the power-broadening of the resonances can be substantially reduced. A density-dependent spectral narrowing of the Electromagnetically Induced Transparency (EIT) window and novel, even narrower, resonances superimposed on the EIT line are observed in dense Rb vapor. A nonlinear two-photon spectroscopic technique based on coherent atomic media and combining high resolution with a large signal-to-noise ratio seems feasible.

iii) Buildup of optical parametric oscillator from quantum noise.

Nonlinear optical parametric processes are studied in a resonantly driven multilevel system displaying quantum interference effects. It is shown that in such systems a new regime of nonlinear amplification is possible, in which a pair of correlated Stokes and anti-Stokes fields can be generated from infinitesimally small initial values. An atomic coherence grating emerges *during* the process of such efficient nonlinear amplification. The present analysis explains the results of recent optical phase conjugation experiments involving atomic phase coherence.

Fundamentals

i) New dynamic theory of Bose-Einstein Condensation.

The ground state of a Bose gas consisting of N trapped atoms at temperature T is analyzed. New analytical results are obtained for the statistical distribution, the average number and variance of the number of atoms in the ground state. The present analysis has much in common with the quantum theory of the laser, and with the laser phase transition analogy.

ii) Intracavity electromagnetically induced transparency.

The effect of EIT on the properties of optical resonators and active laser devices is discussed theoretically. Pronounced frequency pulling and cavity-linewidth narrowing are predicted. The EIT effect can be used to reduce classical and quantum-phase noise of the beat note of an optical oscillator substantially. Fundamental limits of this stabilization mechanism as well as its potential application to high-resolution spectroscopy are discussed.

iii) Mirrorless parametric oscillator.

Quantum properties of a mirrorless parametric oscillator based on atomic coherence in resonant Raman systems are investigated. We show that such oscillator can be used for generation of pairs of Stokes and anti-Stokes fields with nearly perfect quantum correlation and with stable, narrow-bandwidth frequency difference.

iv) Quantum Eraser.

In a recent article entitled "Restoration of interference and the fallacy of delayed choice: Concerning an experiment proposed by Englert, Scully, and Walther" Mohrhoff discussed the issue of timing between the quantum eraser event and detection of atoms as they interfere at a distant screen. Therefore, we set the record straight by presenting a detailed and careful analysis of a quantum eraser experimental setup showing that the experimenter can indeed choose to ascertain particle-like which path information or wave-like interference information even after the atom has hit the screen.

v) Quantum theory of the mazer.

We calculate the spectrum of the micromaser with quantized motion of the pump atoms [M. O. Scully, G. M. Meyer, and H. Walther, Phys. Rev. Lett. 76, 4144 (1996)] in different velocity regimes. We show that when the kinetic energy of the pump atoms is comparable to the atom-field interaction energy the spectrum of the cavity field is no longer centered at the cavity frequency. In the case of very slow atoms huge broadenings and shifts occur in the vicinity of the mazer resonances. We present approximate analytical results for the spectrum that allow a comparison with the exact numerical calculations.

vi) The role of atomic recoil in micromaser "Welcher Weg" detection.

In recent work involving micromaser "which-path detectors" it was shown that the loss of interference in a two slit experiment is based completely on complementarity. The position-momentum uncertainty relation plays no essential role. Storey et al. have argued that the loss of the interference is due to atomic recoil originating in the emission and absorption of microwave photons. This was refuted by Englert et al., who showed that the kicks due to these microwave photons were, to a good approximation, negligible. But the argument continues in a recent Nature article, and that is the reason for this detailed calculation. The result proves that the correlation between detector and measured system, i.e., between micromaser cavities and atom, is the only reason for the loss of interference. Transverse momentum kicks play no role.

vii) Observation of spontaneous emission modification via quantum interference in a ladder atom driven by two coherent fields: a central dip.

Modification of spontaneous emission by quantum interference has been observed for the first time in the general resonance fluorescence of a ladder-type atom driven by two coherent laser fields. Its key feature is that a central dip at frequency $\bar{\omega} = 0$ rather than a central peak demonstrated in many previous works, splits a usual emission spectrum into two halves and each half has the same height and the same width (nearly one half of spontaneous width) if a total Rabi frequency is small enough. A neutral sodium atomic beam was employed in the experiment and an exact solution of the emission spectrum is presented for the resonance case to explain the observed experimental results.

viii) Spectral line elimination and spontaneous emission cancellation via quantum interference

Quantum interference in spontaneous emission from a four-level atom is investigated. The atom has two upper levels coupled by the same vacuum modes to a common lower level and is driven by a coherent field to an auxiliary level. Interference can lead to the elimination of a spectral line in the spontaneous emission spectrum and spontaneous emission cancellation in steady state.

ix) Quenching of spontaneous emission via quantum interference

A four-level atom, driven by a coherent field, is considered. We show that under certain conditions complete quenching of spontaneous emission is possible. Hence the population inversion on some specific atomic transitions can be created using a very weak incoherent pumping. We investigate

the physics of the effect using bare and dressed states. The proposed scheme may be useful, in principle, for generation of high-frequency and/or high power laser light.

- x) On enhancing spectral resolution via correlated spontaneous emission
Correlated spontaneous emission from a single three-level atom in a cascade configuration can yield subnatural line narrowing beyond the usual radiative broadening. The effect is observed in the second-order coherence properties of the radiated field.
- xi) CEL gyroscope with injected squeezed vacuum
We show that the injection of a squeezed vacuum into a correlated emission ring laser gyroscope enhances the sensitivity of the devices. In particular, we demonstrate that if the phase of the injected squeezed vacuum is chosen appropriately then the output is squeezed in the phase quadrature. This may lead to complete suppression of the shot noise in the signal,
- xii) Spectroscopy in Dense Coherent Media: Line Narrowing and Interference Effects
Spectroscopic properties of coherently prepared, optically dense atomic media are studied experimentally and analyzed theoretically. It is shown that in such media the power broadening of the resonances can be substantially reduced. A density-dependent spectral narrowing of the electromagnetically induced transparency (EIT) window and novel, even narrower, resonances superimposed on the EIT line are observed in dense Rb vapor. A nonlinear two-photon spectroscopic technique based on coherent atomic media and combining high resolution with a large signal-to-noise ratio seems feasible.
- xiii) White-light cavities, atomic phase coherence, and gravitational wave detectors.
We propose a new concept to realize optical cavities with large buildup but broadband response (white-light cavities) using atomic phase coherence. We demonstrate that strongly driven double- Λ systems can show negative dispersion without absorption, which is needed in order to compensate for the variation of the wavelength with frequency. Internal buildup profiles and the cavity bandwidth of standard devices and white-light cavities will be briefly compared. These devices may be useful to improve the bandwidth and sensitivity of future generations of laser interferometric gravitational wave detectors.

Impact:

- i) We demonstrated for the first time lasing without inversion in continuous-wave regime in a Rb-cell.
- ii) Laser operation without inversion in a Na-beam with frequency up-conversion was experimentally demonstrated.
- iii) Extensive theory and preliminary data in support of LWI in the blue, and blue-light generation in frequency up-conversion.
- iv) We demonstrated the index enhancement via quantum coherence for the first time experimentally in a Rb cell.
- v) A new regime of nonlinear interactions; first observation of parametric backward self-oscillations via coherent Raman nonlinearities.
- vi) A new approach to high-resolution spectroscopy and magnetometry via atomic coherence effects.
- vii) A possibility of dramatic noise reduction via intracavity EIT.
- viii) A new approach to the theory of Bose-Einstein Condensation (BEC) via a laser phase transition analogy.

(f) Graduate Students and Post docs:

Graduate Students: Chris Bednar, Silke Bermann, Kim Chapin,
Jereomy Faber, Ulf Klinker, Kishore Kapale,
Hwang Lee, Mikhail Lukin, Joe Musser,

Post Doctoral: Dimitri Nikonov, Robert Pfund, Pavel Polynkin,
Cun-Yun Ye, Susanne Yelin.
Michael Fleischhauer, Victor Kozlov, Jia-Ren Liu,
Andrey Matsko, Nikolai Senkov, Vladimir Sautenkov,
Scott Shepard, Yuri Rostovtsev, Abdul Toor,
Dmitri Volchenkov, Alexander Zibrov

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